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Roads & SDGs, tradeoffs and synergies: learning from Brazil's Amazon in distinguishing frontiers

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Abstract
To inform the search for SDG synergies in infrastructure provision, and to reduce SDG tradeoffs, the authors show that road impacts on Brazilian Amazon forests have varied significantly across settings. Forest loss varied predictably with prior development – both prior roads and prior deforestation – and in a spatial pattern suggesting a synergy between forests and urban growth in such frontiers. Examining multiple roads investments, the authors estimate impact for settings of high, medium and low prior roads and deforestation. Census-tract observations are numerous for each setting and reveal a pattern, not consistent with endogeneity, that confirms our predictions for this kind of frontier. Impacts are: low after relatively high prior development; larger for medium prior development, at the forest margin; then low again for low prior development. For the latter setting, the authors note that in such isolated areas, interactions with conservation policies influence forest impacts over time. These Amazonian results suggest 'SDG strategic' locations of infrastructure, an idea they suggest for other frontiers while highlighting differences in those frontiers and their SDG opportunities.

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1. Introduction

Infrastructural investments that lower transport costs can have considerable impacts on many elements of economic development. In terms of Sustainable Development Goals (SDGs), while #9 directly recognizes the roles of infrastucture – also bringing in industrialization and innovation, linked with cities as in #11 – SDGs #1, #2, #3 and #8 all highlight elements of economic development that we would expect to improve via trade, specialization and improved public service delivery if roads networks expand to further connect cities and rural areas (see van de Walle 2002, Andersen et al. 2002, Khandker et al. 2009, Warr 2010, Bell and Van Dillen 2012, Aggarwal 2014, Gollin and Rogerson 2014). This drives many planned expansions.

Expansions of roads networks also affect land use in ways that affect not only life on land (#15) but also life below water (#14), given strong direct connections via runoff plus enormous impacts through atmospheric conditions, including those likely to influence the climate (#13). Thus, the possible tradeoffs − and perhaps synergies − in road infrastructure are considerable. So too are planned future investments globally of up to 25m km by 2050 (Caro et al. 2014; Laurance et al. 2014, 2015; Wade 2017 on 'OBOR').

Scanning the empirical roads literature suggests that roads have an obvious and constant tradeoff. Roads are found to be one of the most consistent and largest factors in deforestation within studies to date and particularly within the tropical frontiers (Angelsen and Kaimowitz 1999, Pfaff 1999 and 2007, Geist and Lambin 2002, Rudel et al. 2009, Ferretti-gallon and Busch 2014). That makes sense for the settings considered, in which roads have lowered input costs and raised farmgate prices for agropastoral outputs to expand the areas in which agriculture is profitable, leading to deforestation (see, e.g., von Thünen 1826).

However, this paper's goal is to empirically distinguish settings, even for a given forest frontier, to highlight that the forest loss a society must incur as a tradeoff for an economic gain is not constant but, instead, varies considerably. We closely analyze the forest impacts of roads on a specific forest frontier − the Brazilian Amazon early in its development. This informs infrastructure choices for specific other sites, while more generally demonstrating the importance of different settings for SDG tradeoffs and synergies. We conclude, within our Discussion, by distinguishing this particular forest frontier from other key forest frontiers, which seem different *a priori* and for some of which impacts of new roads have been examined.

For the Brazilian Amazon, potential tensions between the foci now represented in different SDGs have long been clear − for a region of high biodiversity whose forests play roles in carbon and hydrologic cycles. In the early 1960s, the Brazilian government began to build roads to link to other parts of Brazil, and within decades over 10% of this forest was cleared, with annual loss in the millions of hectares (see, e.g., INPE 2016). From the early 2000s, there have been calls to pave roads for development objectives, including the expansion of soybean exports (Laurance et al. 2001, Fearnside 2001, Nepstad et al. 2002).[1]

For such new road investments, instead of simply estimating their average impacts on the forest we start by modeling roads' impacts as a function of prior development. The differentiated predictions guide empirical tests of significant variation in roads' impacts on forest frontiers as this region developed. Such variation in impacts would suggest that shifting road locations could generate cleaner development.

For early frontier days, we believe the classic, von Thunen market-center model is appropriate for consideration of three different contexts that are distinguished by their market distance and profitability. Others have long used this model for early frontier development[2], though not for *variation* in road impact.

This model predicts that increased deforestation due to a new road is low if, given other factors, prior roads already led to significant prior deforestation. For intermediate levels of prior development, roads are predicted to generate more deforestation, as more parcels are 'at the margin' of profitability. Finally, the model predicts little short-run deforestation impact of new roads within the distant, isolated and currently undeveloped frontiers (for this setting, we discuss long versus short run and other policies[3]).

Thus, this model predicts lower, then higher, then lower road impacts as prior development falls. Such a pattern would not be generated by the endogeneity of roads' locations to more profitable locations. While if new roads go to sites with unobservable drivers of deforestation it could indeed bias each of our impact estimates, that sort of selection for investment would not predict the pattern of impact that we find.

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[1] While much of the Brazilian Legal Amazon is naturally primary forest and remains so, the region includes large areas of *cerrado* (or savannah). To date, the expansion of soy production has been concentrated within those areas.

[2] Given other settings of economic development and deforestation we must mention analyses such as Mather (1992), Foster and Rosenzweig (2003), Chomitz (2006) and recently, adding road empirics to their overlap, Kaczan (2016).

[3] For a few years to a decade, i.e., the typical time period for deforestation studies, far out on the frontier labor and other inputs can be insufficient to permit large rapid changes. The long run can be much the same or very different.

Unlike almost all of the current work in the literature (though fortunately this is being remedied), our data include roads changes over time and, in fact, two such sets of roads investments that were made before the periods (1976-1987, 1986-1992) of deforestation that we are trying to explain. The periods are, by design, part of early development on this Amazon frontier. They permit results concerning dynamics in early growth, i.e., for one important type of frontier dynamic. (Again, our Discussion considers others.)

To have sufficient observations for each prior-development setting on this early Amazon frontier, as observations we use census tracts − considerably smaller than the county units often studied for Brazil. For 1976-1987 clearing, they confirm the short-run predictions from our model. Forest impact is close to zero from the new roads in the regions with the highest prior development. In regions with intermediate levels of prior development, however, the deforestation following the new road investments is significant. Finally, for regions of low prior development, new roads generate little deforestation across this period.

For 1986-1992 deforestation, again we can confirm predicted spatial variations in roads' impacts. Specifically, for higher past development again we see low impact and for intermediate past development – which rises with ongoing development – again we see higher impact. For 'low prior development', our results for this later time period depend on how we define it. Defining 'low' as zero prior deforestation, which summarizes all influences, again new roads have small, even statistically insignificant impacts on deforestation. To stress the importance of understanding relevant evolutions during ongoing development, though, we also show that if defining 'low prior development' using low prior roads alone, i.e., ignoring other relevant elements of ongoing development, these new roads' impacts are as high as the road impacts with intermediate prior development. Thus, we can see that any region, such as the Brazilian Amazon, clearly will evolve over time in ways that affect the SDG tradeoffs involved in infrastructure investments. That said, the policy relevant differences in roads' impacts by level of prior development are quite robust.

The rest of the paper is as follows. Section 2 reviews prior work concerning impacts of roads − for SDG purposes including economic effects, both aggregate and on poverty, as well as forest impacts. Section 3 presents our derivation, based on the von Thunen (1826) model, of predicted impacts variations. Section 4 presents our data and specification, Section 5 discusses all our results, then Section 6 concludes.

2. Relevant Frontier Variation

2.1 Varied Road Benefits

If road's economic (or more generally development-SDG) benefits were uniform, roads' deforestation impacts might determine optimal locations. However, benefits may vary. For the Brazilian Amazon, e.g., Andersen et al. (2002) find in census data that economic impacts may be higher where prior development is higher, e.g., near cities. This opens the door to SDG synergies from the choice of new roads' locations: if forest loss is lower in such areas, new roads near prior development may maximize total gains in SDGs.

Varied rural road benefits are a focus in van de Walle (2002). Evaluations focused on total travel time or output, not distinguishing groups by poverty, are criticized for leaning towards developed areas. Rural roads may generate less of the kinds of benefits that tend to be counted officially, yet more of the benefits that tend not to be. Illustrating this for Vietnam stresses the value of identifying, with sufficient resolution (linking to a data point in our conclusion), whether a new road improves access for each group.

Gibson and Rozelle (2003) also ask where benefits are high. They consider Papua New Guinea, where terrain and history yield transport gaps, and stress that understanding where road access is a factor in poverty helps to target impact. Their focus on access, and poverty objective, motivate attention to rural frontiers. Examining rural areas with relatively low prior development, with or without an instrument for roads, their evidence suggests that roads reduce poverty if the prior access to infrastructure has been low.

Warr (2005)'s evidence for rural road benefits highlights a positive interaction between economic reforms and access to markets. It distinguishes year-round market access from only during dry seasons, finding that raising access in wet seasons lowers poverty. Reducing poverty is again the central objective, which is noted to differ from maximizing benefits in the aggregate, such that the objective affects relative measured benefits across the road options in question. Methodologically, road changes are suggested, to address endogeneity in road siting − in agreement with our emphasis on building up intertemporal data.

2.2 Varied Species Densities

If economic benefits and deforestation impacts were uniform, then arguments drawn from early literature on conservation about variations in species benefits might determine optimal road locations.

Road planning could place different weights on forest parcels. A minimal review of such literature may differentiate 'scoring', 'iterative', and 'programming' approaches to maximizing species benefits. 'Scoring' ranks each site, by contribution to the objective, then proceeds down a ranked list.[4] This allows inefficient duplication, however. 'Iterative' analyses avoid duplication by ranking marginal contributions conditional on prior protection: the top-ranked site is protected; and then all the other sites are re-ranked.[5] 'Programming' approaches uses standard operations-research techniques.[6] Unlike sequential approaches, they compare entire choice sequences so that earlier choices are evaluated in light of later choices of sites.

2.3 Varied Deforestation Impacts[7]

For the Brazilian Amazon, Almeida (1992) examine colonization and migration, while Reis and Margulis (1991) and Reis and Guzman (1992) also find roads to be key drivers of deforestation. Pfaff (1999) adds that population's spatial distribution (and thus urbanization) is critical, while roads matter not only within but also across counties.[8] Laurance et al. (2001)'s discussion of deforestation from roads has an 'optimistic' scenario with loss of 28% of pre-Columbian forest by 2020 (42% lost in a 'non-optimistic' scenario). Such work stimulated debate about assumptions for average and heterogeneous roads impacts.

Heterogeneous impacts can explain why average impact estimates have not always been large (Chomitz and Thomas 2003 for Brazilian Amazon). Nelson and Hellerstein (1997) explicitly suggested that impacts may vary across space. For central Mexico, they find that the existence of prior roads in an area influences road impact. Thus, average impact could misrepresent every setting. Alongside Chomitz and Thomas (2003)'s observations, we must ask if average impacts understate some higher roads impacts.

[4] See Tubbs and Blackwood (1971), Gehlbach (1975) and Williams (1980) for examples of this approach.

[5] Kirkpatrick (1983) as well as Saetersdal et al. (1993), among others, provide discussion of this approach.

[6] Cocks and Baird (1989), Church et al. (1996) and Csuti et al. (1997) provide helpful examples of this approach.

[7] A first empirical wave (Lugo et al. 1981, Allen and Barnes 1985, Palo et al. 1987, Cropper and Griffiths 1994 and Deacon 1994 − with reviews in Kaimowitz and Angelsen 1998 or Geist and Lambin 2001) could not focus on roads, given limits on comparable data across countries. Central results concerned population, the most available variable. Controlling for more factors is important. Panoyotou and Sungsuwan (1989) find that Thai deforestation is driven by population, wood price, income, and market distance. Southgate et al. (1991), for Ecuador's Amazon region, explain population with "the prospect of agricultural rents" and then explain deforestation with population and other factors.

[8] Around this time, using similar approaches, Chomitz and Gray (1996) study roads and deforestation within Belize, Nelson and Hellerstein (1997) study these issues within central Mexico and Cropper et al. (2001) consider Thailand.

Andersen et al. (2002) pursue heterogeneous impacts of roads by studying Brazilian census data. They ask if impacts vary with past deforestation, using an interaction effect such that higher deforestation has monotonic impact. This contributed in approach and the result is consistent with one of our results.

That estimated interaction also means that high enough prior deforestation implies that new roads reduce deforestation. Weinhold and Reis (2008) extend this claim empirically and by suggesting spatial intensification: development is drawn to roads, so it falls in places near to but without an own new road. Refuting that hypothesis, Pfaff et al. (2007) show that nearby census tracts[9] not receiving new roads, yet in the same county as a census tract that did receive a new road, actually increased in their deforestation.

Another economic interaction that might underlie such empirical associations for forests is trade. In the New England region within the United States (Pfaff 2000 and Pfaff and Walker 2010), for instance, investing in railroad connections to the Midwest raised New England forest, as agricultural production fell in the latter given more efficient Midwest production. Pfaff and Walker (2010) suggest that analogous rising net imports will not soon save Amazon forests. Our model is a different economic story for forest impacts of roads, one conditioned on prior development and not suggesting that roads lower deforestation.

3. Modeling Road Impacts

3.1 Prior Development Landscapes

Our modeling follows von Thunen (1826) per where we expect clearing for agricultural development. One agricultural good is produced. All land extends out from a market, is originally forested, and remains so until cleared for agriculture. One unit of agricultural good is produced in each location, *i*, yielding agricultural profit $\pi_i = P - t_i - c_i - \varepsilon_i$, where: P is the output price at market; t_i is transport costs to market from *i*; c_i is the cost of production per unit of output in parcel *i*; and ε_i is an identically and independently distributed random term that represents unobservable factors favoring forest profits over clearing profits.

For modeling deforestation empirically, the random term provides an indication of factors beyond market price and transport costs. Key factors include soil quality, land slope and local policy. Above, c_i

[9] Lacking census-tract detail implies at most 300 *municipio* or "county" units for study over time. That limits study of heterogeneity, in particular for Brazilian Amazon counties that can be huge, making the data for county units misleading for census tracts. Figure 1 shows how different are the census tract and county representations of a road.

indicates observable elements of those determinants, some of which we include in our empirical analyses. Unobservable elements are denoted by the random term ε_i. For our empirical work, that motivates error terms. We reflect their potential importance in model predictions (Figures 2 and 3) and in interpretations.

Profit maximization implies a probability of any given parcel being cleared in static equilibrium:

$$\Pr(P - t_i - c_i > \varepsilon_i) = \Phi(P - t_i - c_i) \quad ,$$

where Φ is the cumulative function for a single-peaked distribution with mean and peak at zero. Figure 2 -- assuming a common c_i -- shows how the probability of deforestation falls as t_i rises. Highly varied prior development and deforestation are seen in three zones distinguished by 'Expected Profits': 1) high prior development near market center; 2) forest margin where expected profits are zero and parcels are near the margin; and 3) low prior development farther from the market center on isolated, less developed frontiers.

3.2 Short-Run Road Impacts

Road investments lower transport costs, so that we expect land-use change. The first derivative of the probability of deforestation at i with respect to t_i indicates heterogeneous impacts on deforestation:

$$d\,\Pr(P - t_i - c_i > \varepsilon_i) \;/\; d\,t_i \quad = \quad \varphi(P - t_i - c_i)(-1) \quad .$$

Figure 3 conveys this prediction. The impact of a transport-cost reduction is ϕ. It depends on the density of parcels that become profitable with a road and, thereby, on where was the prior land-use equilibrium.

Most striking is the non-monotonicity of the impacts of new roads. Impact is low where there was higher prior development and deforestation, nearer to the market center (low transport costs in Figure 3), since most forest is cleared before the investment. Impact is low also for low prior development and low prior deforestation, farther from market (to the right in Figure 3), since marginally reducing transport costs makes newly profitable only the few parcels with random terms that highly favor profit in clearing.

Near 'the von Thunen forest margin', where expected net profits are close to zero and there is an intermediate level of prior development and deforestation, many parcels may become newly profitable due to a road investment, yieldig higher road impact. Such a pattern of new roads' marginal impacts on deforestation follows directly from single-peaked distributions of the random term. A uniform distribution yields zero impact in either tail but a positive and uniform impact within the support (relative to which a standard von Thunen model with no land-quality variation simply shrinks the range with impacts). Thus, for many settings, roads' predicted short-run impacts will vary non-monotonically with past development.

3.3 Longer-Run Development Dynamics

After a road better connects a frontier, public and private investments may follow (yet data sets may well not include them). Settlers will lobby locally for additional roads, schools, agricultural subsidies and other investments that raise their quality of life. Investments, in turn, affect decisions by migrants and producers. Dynamic interactions, likely with path dependence between public and private decisions, then affect forest outcomes (and such processes could have impact beyond the location of the road investment, which empirically means beyond the unit such as a census tract in which investment occurs (Pfaff 2007)).

Thus, frontier conditions change as development unfolds, again perhaps in ways not captured in data sets. Prior road investment nearby, e.g., may lead to unpaved road extensions in census tracts that we may not observe yet nonethless raise deforestation. Thus, nearby prior roads may indicate such processes. By our second time period, we might expect more unobserved improvements that facilitate development. Thus, we want to examine new roads' impacts by time period (as is supported by data differences below).

4. Data & Specifications

4.1 Data

We use census tracts to have more observations than the counties in many Brazilian Amazon analyses (Reis and Guzman 1992, Pfaff 1999, Andersen et al. 2002, Weinhold and Reis 2008). This increases our cross-sectional units from under 300 to over 6000 − extremely helpful because to address spatial variation in road impacts, our intended focus, we want to be able to estimate more than just a single average road impact. Table 1 presents statistics for these smaller sampling units that, on average, are under 1000 km^2.

4.1.1 Deforestation

We examine measures of the deforestation during 1976-1987 and 1986-1992. For the first period, the maps we used were produced in 1997 by the IBGE (Instituto Brasileiro de Geografia e Estatistica) for their “Diagnostico Ambiental da Amazonia Legal” data product. Our 1976 forest cover is from RADAM

Project vegetation maps. The forested area information for 1987 is from IBAMA/INPE maps based upon Landsat imagery. For our second time period, the 1986 and the 1992 forest observations were generated by the TRFIC (Tropical Rain Forest Information Center, www.trfic.msu.edu/products/amazon_products/), located at Michigan State University, and are derived from Landsat data with a spatial accuracy of 1km.

For a given census tract, at any point in time we know the fraction of area in forest. To compute deforestation by 1976 required a map of the original extent of forest in each census tract (as noted earlier, significant areas were not originally forest). Our 'Deforestation 1976' variable is the fraction of original forest area gone by 1976. Similarly, for each period, our dependent variable (fraction of the forest cleared during the period) is computed from the loss of the forest area that was present at the start of the period.

4.1.2 Roads

We tracked roads changes over time from highly spatially specific maps. Digital road maps were developed at the Department of Geography at Michigan State University from paper maps by DNER (Departamento Nacional de Estradas de Rodagem), an agency within the Transport Ministry in Brazil. For each census tract for 1968, 1975 and 1985, we measure paved-road and unpaved-road density, i.e., length divided by the census tract's area. This permits initial road measures before investments and two periods of changes. We emphasize that our time periods for measuring road changes each come before the periods of deforestation. As Warr (2005) notes, using road changes is particularly useful for helping to address the issue of endogenous road placement. Having road changes come before forest changes helps even more.

We had measures of road investments in neighboring census tracts for our first investments, i.e., the 1968-1975 roads changes. To check robustness, to this we added neighboring-tract road investments for 1975-1985. For each census tract, and time period, we have indicators for whether a tract in the same county received road investments (in 100km rings around the tract in question). These help to distinguish, from among many census tracts that feature relatively low prior development – again that is measured using prior roads and prior deforestation − where the new investments in roads truly are the most isolated.

4.1.3 Other Factors

We control for distances from the census-tract centroids to cities. We use both a set of 19 large cities ('large' defined as a density over 100 people/km^2) as well as another set of 270 medium and large cities ('medium' defined as a density over 11 people/km^2). We include these urban or market distances as variables in our regressions − but also, wanting to focus upon the settings where deforestation is highly relevant, we use the city distances in various ways to drop some urban areas in order to check robustness.

We have maps of biophysical conditions. The variables we employ are an index of soil quality, a continuous measure of rainfall data (see Laurance et al. 2002 for discussion, as well as the original extent of the forest) and binary variables that indicate categories for land slope (e.g., whether land is 'steeply sloped' land or 'rolling hills'). Finally, we also include county indicator variables to help to control for all of the unobservable county characteristics. This provides controls for the many possible differences, such as price and production costs, which vary by county but are common across the census tracts in a county. These controls are made possible by the census-tract data and are very useful given the size of this region.

4.2 Specifications

4.2.1 Core Specification

Since the census tracts are quite varied in their areas, and we want results for an average forest parcel facing the threat of clearing, we weighted the following regression using census tracts' forest areas:

$$\%Deforest_{t,t+1} = \beta_0 + \beta_1 * RoadsInvestment_{t-1,t} + \beta_2 * PriorRoads_{t-1} + \beta_3 * PriorDeforestation_t$$
$$+ \beta_4 * CityDistance + \beta_5 * Soil + \beta_6 * Rain + \beta_7 * Slope + \beta_8 * County + \varepsilon .$$

It is worth reiterating how our data permit progress on identification of roads' impacts. Deforestation is change over time in the forest outcome of interest, measured across each of our two time periods. However, while many analyses have used forest-change measures, many fewer have had in hand changes in the roads over time, i.e., road investments as opposed to just a road's presence within a unit. Without such changes, i.e., with just a snapshot of a road at a point in time, we do not know when any given road came to be present and, thus, whether we should expect its presence to have ongoing effects.

That our road changes are for periods before the forest changes eliminates the possibility that roads responded to the deforestation we are trying to explain. It is, of course, possible that road creation was forward-looking, e.g., developers picked regions where future economic activity and deforestation were expected. However, even if so, county dummies provide a partial remedy. Because road-investment impacts are estimated using within-county variation across tracts, in order to bias our roads coefficients such endogeneity driving road location would have to be picking out particular census tracts in a county.

4.2.2 Prior Development

Our specification above indicates that we always control for prior roads and deforestation. When we move to a focus on heterogeneous impacts, we expect road impacts to vary with prior development. Here we discuss the rules we use to split levels of prior development. We can use them to split our sample or to interact prior development categories with roads investments. All our rules are based on prior roads and prior deforestation, noting that deforestation is of course a more comprehensive summary of a setting.

We chose initial definitions of higher, intermediate and lower prior development *a priori*, without looking at the data, i.e., simply trying to think about what might characterize such levels of development. One natural option was that 'lower prior development' would mean no prior roads or prior deforestation, while 'higher prior development' would mean somehow having both prior roads and prior deforestation.

To better distinguish settings, we defined 'higher prior development' as tracts with prior roads plus prior deforestation of over 25%. Correspondingly, we defined 'lower development' as no prior roads but deforestation up to 25%. For results tables, we arrange the census-tract groups from highest prior development to lowest. Thus, "High Prior Dev1" is the stricter definition above that requires greater prior deforestation. For our ordering, the smaller strictly defined group of low tracts will be "Low Prior Dev2".

For robustness, we also considered other rules such as 12.5% prior deforestation for both ends of the spectrum and, as always, 'intermediate' in the middle (i.e, the tracts with no prior roads above 12.5% prior deforestation and the tracts with prior roads below 12.5% prior deforestation). For all these divisions to check robustness we used different rules to drop tracts based on distance to city including: within 30km of a city; within 5km of a medium city; and within 10km of a large city. All our broad results are robust.

Finally, we note that our 'lower prior development' range had many tracts (i.e., over two thirds). To distinguish among these tracts, we shrank the 'lower prior development' category by including only tracts with no prior neighboring investments either. This makes the 'intermediate' category larger, since some relatively higher 'lower prior development' tracts move up. This sometimes shifted the impacts but often did not. Importantly, it dramatically shrunk the 'lower' group, often to reveal a smaller road impact.

5. Results

5.1 Road Impacts on 1976-1987 Deforestation

5.1.1 Average Impacts of 1968-1975 Road Investments

On average, road investments increase deforestation in this time period. Table 2's first column shows a highly significant impact from increasing road density, even controlling for the road density before investment. That prior density is highly significant as well, as is the total prior deforestation. We stress that inclusion of these elements of prior development provides quite strong controls for new roads.

This column also confirms important controls for inferences concerning new road investments, as greater market distance discourages deforestation while higher soil fertility increases it. Rainfall and slope also significantly constrain economic production and thus deforestation. Yet county dummies absorb the spatial variation that could, in principle, be used for estimating the effects of those variables (for instance, without the counties all of the rainfall terms are significant, with linear terms positive and quadratic terms negative). Therefore, across our tables we simply indicate that we control for counties, rainfall and slopes.

5.1.2 Road Impact By Prior Development

For the small set of 'higher prior development' tracts, Table 2's second and third columns convey that road investments did not significantly raise deforestation. That holds for both definitions of 'higher' in Table 2, as well as for the robustness check that employed 12.5% for prior deforestation (not shown).

Few 'higher prior development' tracts describes the early state of this frontier. It limits our tests but as a robustness check we can interact continuous 'prior development' with road investment (Table 3, columns 1 and 2). Given our non-monotonic prediction, we interact with our continuous road changes both linear and quadratic prior road density. as well as both linear and quadratic prior deforestation.

Neither prior-deforestation term is significant, nor is the quadratic prior-roads term (1st column). Thus for easier interpretation, the 2nd column includes only the significantly negative linear term for the interaction of prior road density with road investments. This supports the conjecture that higher prior development reduces new roads' impacts. (We cannot test the low category this way as many tracts had no prior roads.)

For 'intermediate prior development', Table 2's 4th and 5th columns show our quite robust results. Generally, we find new roads' impacts similar to the average impact for the entire set of census tracts. Supporting our model, 'intermediate' impact is above the 'lower' impact (6th and 7th columns) and also above the 'higher' impact (2nd and 3rd columns but, again, better illustrated by Table 3's columns 1 and 2).

Table 2's 6th and 7th columns illustrate the lack of significant impact even for the large groups of census tracts that qualify under our two definitions of lowest prior development. Recall, when we used the absence of prior roads and prior deforestation, over two-thirds of our sample qualified. Thus, in order to identify some census tracts with even lower relative prior development, we dropped those tracts that had any neighbor-tract road investments, out to 100km (6th column) or even 200km (7th column) from a tract. For this time period, then, we have sufficient observations to test impact for very low prior development.

5.2 Road Impacts on 1986-1992 Deforestation

5.2.1 Average Impacts of 1975-1985 Road Investments

In this period too, on average, new roads increased deforestation. In Table 4, like Table 2, the first column has average effects and new roads are significant even with controls for prior road densities and deforestation. Again like in Table 2, Table 4's first column includes many other variables that function as controls. Thus again, for a second time period, we see impacts from roads even with very strong controls.

Yet Table 4's estimate is one-eighth of that in Table 2. This supports our conjecture about the challenge in comparing across time periods, given significant shifts in any given setting including shifts common across this region such as exchange rates, diseases such as hoof-and-mouth, and the status of national and global economies. Below, we look within this time period, across prior development levels.

5.2.2 Road Impact By Prior Development

Table 4's second column, for the stricter definition of 'high prior development', conveys that development has occurred through its number of observations. The set of census tracts that qualify for the stricter 'high prior development' category is roughly five times as large as for the first period. Supporting the strongest version of our predictions, even for this larger strict group in the second period we find that roads have little or no impact. This supports that high prior development lowers new roads' forest impacts – also supported by negative effects for our new-road interactions with prior roads in Table 3 (column 3).

Table 4's third column also conveys development over time through its number of observations. For this less strictly defined 'high prior development', now roughly ten times as many tracts qualify. However, within this larger group of tracts, given a less strict definition, we now find significant new road impact (though lower than the average impact, so still consistent with a weak version of our predictions).

Table 4's fourth and fifth columns confirm our prediction about significant impacts of new roads within the 'intermediate prior development' category. Again, as before, this group of tracts has impacts similar to the average impact in Table 4's first column. This middling-prior-development result is robust.

Yet our two definitions of 'lower prior development' within Table 4's sixth and seventh columns tell different stories. The difference suggests rises across time in unobservable elements of development. When 'lower prior development' is defined solely by lower prior road density, development can be driven ahead by other factors including ones we do not observe. Despite the observed lower prior road density, other factors could raise road impacts. We find impact similar to 'intermediate' despite no prior roads (6^{th} column). Yet if there is no prior deforestation within 'lower', results still fit our prediction of no impact (7^{th} column). The set of such census tracts is shrinking, showing the value of studying early development.

Further support for our predictions is provided by interactions. Within the 3^{rd} column of Table 3, both interactions with prior deforestation are significant (prior deforestation's greater influence in the 2^{nd} period supports conjectures above). The positive linear interaction with the negative quadratic interaction suggest exactly that new-road investments raise deforestation most for 'intermediate' prior deforestation. Finally, with sufficient observations in each 'prior development' category for this period, we supplement results from Table 4 by interacting categories with roads in Table 3 and we find support across the tables.

6. Discussion

To demonstrate policy relevant variations in the SDG tradeoffs involved in road infrastructure, we tested a prediction of variation in roads' forest impacts during early Brazilian Amazon development. We confirmed predictions from a model of agropastoral expansion, i.e., that deforestation from new roads at first rises then falls with prior development: smaller impact where high prior development already has occurred; larger impact at forest margins; then smaller impact again for the isolated, undeveloped frontier.

As the prior development indicators we used are easily observable by policy makers, such results suggest that in siting transport infrastructure the tradeoffs between SDGs could be considerably reduced. Further, combining these results with others' results concerning new roads' impacts on economic growth suggests that both urban growth and standing forests could benefit from targeted patterns of investment (adding ecological variation in forest benefits could, of course, inject further rationales for road locations, as commonly suggested including recently by Mahmoud et al. 2017 for a proposed highway in Nigeria).

These results about dynamics on relatively isolated frontiers are relevant for specific other sites. Yet while highlighting that these varied impacts offer an opportunity for policy, it is critical that we also emphasize that the opportunities for SDG optimization in road location will vary with the type of frontier. Our results indicate this with shifts over time in whether low prior roads identify low prior development. More generally, ongoing development in frontiers like the Amazon will shift the mix for policy impacts.

For forested locations with longstanding higher development, for instance, the tradeoffs for SDGs within road siting clearly differ. For instance, Kaczan (2017) considers India and a post-2000 program of investment in rural roads. There, not only is forest rising across decades but also, on average, new roads slightly raised forest cover. That too can make sense, given completely different mechanisms or behaviors affected by transport costs. However, breaking down such an average again is very informative for policy. For the locations in India that are more isolated, i.e., more like some of the Latin American forest sites very present in past roads literature, roads once again lower forest cover. Yet within those parts of India that feature much greater ongoing development, in fact new roads more significantly raised forest cover. Going forward, understanding these differences in frontiers will be critical within the pursuit of the SDGs.

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Table 1

Descriptive Statistics *

VARIABLES	Mean	Std. Dev.	Minimum	Maximum
Forest Fraction Cleared 1976-87	0.22**	0.36	0.00	1.00
Forest Fraction Cleared 1986-92	0.02	0.04	-0.17	0.17
Road Density Increase 1968-75	0.01	0.07	-0.11	2.31
Road Density Increase 1975-85	0.02	0.15	-1.00	8.08
Road Density 1968	0.01	0.04	0.00	1.09
Road Density 1975	0.02	0.12	0.00	4.12
Deforestation 1976	0.07	0.20	0 .00	1.00
Deforestation 1986	0.12	0.22	0.00	1.00
Soil Fertility	2.97	1 .11	0.00	5.00
Distance To Large City	817	456	13	1,783
Distance To Medium City	182	140	0	777
Distance To Small City	132	98	0	524
Distance To River	262	291	0	1,073
linear Rain	2,079	431	1,200	3,969
‘rock outcropping’ Slope	.002	.029	0.00	1.00
‘steep’ Slope	.002	.034	0.00	1.00
‘mountainous’ Slope	.043	.143	0.00	1.00
‘strongly hilly’ Slope	.040	.141	0.00	1.00
‘hilly’ Slope	.125	.262	0.00	1.00
‘gently hilly’ Slope	.326	.373	0.00	1.00

* These statistics all are for the 5372 observations in the first column of Table 2 below, except for the 1986-1992 deforestation, 1975-1985 new roads, 1975 road density, and 1986 deforestation, which are computed for the 6890 observations considered in the first column of Table 4 below.

** Averages are unweighted. Weighting by forest area makes this 0.03 (with 0.004 for 1986-92).

Table 2

Explaining 1976-1987 Deforestation with 1968-1975 Investments, by Prior Development

WEIGHTED OLS**	Average Effects {1}	High* Prior Dev1 {2}	High* Prior Dev2 {3}	Int.* Prior Dev1 {4}	Int.* Prior Dev2 {5}	Low* Prior Dev1 {6}	Low* Prior Dev2 {7}
Road Investments 6875 Density Rise	0.99 (.00)	1.10 (.46)	-0.13 (.83)	1.00 (.00)	1.06 (.00)	-.57 (.84)	-0.20 (.92)
Road Density 1968	1.39 (.00)	0.58 (.30)	0.77 (.16)	1.33 (.00)	1.43 (.00)	--- (--)	--- (--)
Deforestation 1976	0.38 (.00)	0.04 (.73)	0.42 (.00)	0.43 (.00)	0.46 (.00)	0.19 (.21)	--- (--)
Fertility of Soil	0.02 (.00)	0.05 (.04)	0.07 (.00)	0.03 (.00)	0.03 (.00)	0.02 (.00)	0.02 (.33)
Distance To A Large City ***	-0.07 (.00)	-1.53 (.01)	-0.17 (.50)	-0.10 (.00)	-0.09 (.00)	-0.02 (.18)	0.00 (.42)
Constant	0.66 (.04)	13.6 (.89)	-22.9 (.38)	0.16 (.74)	0.60 (.16)	0.24 (.63)	0.17 (.55)
Other City Distances	yes	yes	yes	yes	yes	yes	yes
Distance To River	yes	yes	yes	yes	yes	yes	yes
Rainfall (quartic)	yes	yes	yes	yes	yes	yes	yes
Slope Categories	yes	yes	yes	yes	yes	yes	yes
Counties	yes	yes	yes	yes	yes	yes	yes
R^2	0.31	0.97	0.71	0.34	0.30	0.18	0.09
N	5372	76	159	3650	4334	1640	731

* High Prior Development: in Dev1, prior roads and prior deforestation is > 25%; in Dev2, any prior deforestation.
Intermediate Prior Development: always defined as all of the tracts with lower than 'High' but higher than 'Low'.
Low Prior Development: in Dev1, no prior roads, prior deforestation up to 25%; in Dev2, no prior deforestation.
For neighbor investment: in Dev 1, none in tracts with centroids <= 100km; in Dev2, none in tracts out to 200km.

** Dependent Variable = forest hazard rate = area deforested 1976-1987 divided by tract's initial (1976) forest area. Weights are the tracts' initial forest areas. Regression coefficients are presented with pvalues in the parentheses. Dropping all of the census tracts with centroids within 5km of any of the locations that we define as a large city.

*** coefficient multiplied by 1000 (per kilometer instead of per meter)

Table 3

Explaining 1976-1987 Deforestation and 1986-1992 Deforestation with Interactions (Road Investments x Prior Development Proxies)

WEIGHTED OLS*	1976 -1987 Defor. {1}	1976 -1987 Defor. {2**}	1986 -1992 Defor. {3}	1986 -1992 Defor. {4}	1986 -1992 Defor. {5}
Road Investments, 7585 Density Rise	1.24 (.00)	1.19 (.00)	0.11 (.00)	0.11 (.00)	0.13 (.00)
Road Investments x Prior Road Density	-47.0 (.01)	-0.33 (.00)	-0.10 (.25)		
Road Investments x Prior Road Density^2	166 (.41)	--- (--)	-0.002 (.01)		
Road Investments x Prior Deforestation	0.03 (.99)	--- (--)	0.46 (.00)		
Road Investments x Prior Deforestation^2	-1.47 (.66)	--- (--)	-1.14 (.00)		
Road Investment x High*** Prior Dev				-0.10 (.03)	-0.06 (.01)
Road Investment x Low*** Prior Dev				0.05 (.01)	-0.18 (.15)
All Controls	yes	yes	yes	yes	yes
R^2	0.32	0.32	0.37	0.37	0.37
N	5372	5372	6890	6890	6890

* Dependent Variable = forest hazard rate = area deforested 19xx-19yy divided by tract's initial (19xx) forest area. Weights are the tracts' initial forest areas. Regression coefficients are presented with pvalues in the parentheses. Dropping all of the census tracts with centroids within 5km of any of the locations that we define as a large city.

** For this regression, prior roads' interaction with investment multiplied by 100 to be at same scale as investment.

*** High Prior Development: in {4}, prior roads and prior deforestation is > 25%; in {5}, any prior deforestation.
Intermediate Prior Development: always defined as all tracts with lower than 'High' but higher than 'Low'.
Low Prior Development: in {4}, no prior roads, prior deforestation up to 25%; in {5}, no prior deforestation.
For neighbor investment: in {4}, none in tracts with centroids <= 100km; in {5}, none in tracts out to 200km.

Table 4

Explaining 1986-1992 Deforestation with 1975-1985 Investments, by Prior Development

WEIGHTED OLS**	Average Effects {1}	High* Prior Dev1 {2}	High* Prior Dev2 {3}	Int.* Prior Dev1 {4}	Int.* Prior Dev2 {5}	Low* Prior Dev1 {6}	Low* Prior Dev2 {7}
Road Investments, 7585 Density Rise	0.12 (.00)	0.01 (.87)	0.08 (.01)	0.12 (.00)	0.13 (.00)	0.12 (.00)	0.02 (.60)
Road Density 1975	0.10 (.00)	0.07 (.03)	0.12 (.00)	0.12 (.00)	0.05 (.05)	--- (--)	--- (--)
Deforestation 1986	0.01 (.00)	-0.08 (.00)	0.00 (.74)	0.00 (.39)	0.01 (.05)	0.07 (.00)	--- (--)
Fertility of Soil	0.00 (.49)	0.01 (.02)	0.00 (.53)	0.00 (.30)	0.00 (.46)	-0.00 (.87)	0.00 (.64)
Distance To A Large City ***	0.01 (.00)	0.05 (.02)	0.02 (.01)	0.01 (.00)	0.01 (.00)	0.004 (.06)	-0.00 (.98)
Constant	0.07 (.04)	4.22 (.05)	0.05 (.66)	0.11 (.03)	0.06 (.23)	0.26 (.00)	-0.04 (.35)
Other City Distances	yes	yes	yes	yes	yes	yes	yes
Distance To River	yes	yes	yes	yes	yes	yes	yes
Rainfall(quartic)	yes	yes	yes	yes	yes	yes	yes
Slope Categories	yes	yes	yes	yes	yes	yes	yes
Counties	yes	yes	yes	yes	yes	yes	yes
R^2	0.37	0.58	0.44	0.34	0.36	0.53	0.11
N	6890	339	1149	3896	4675	1674	448

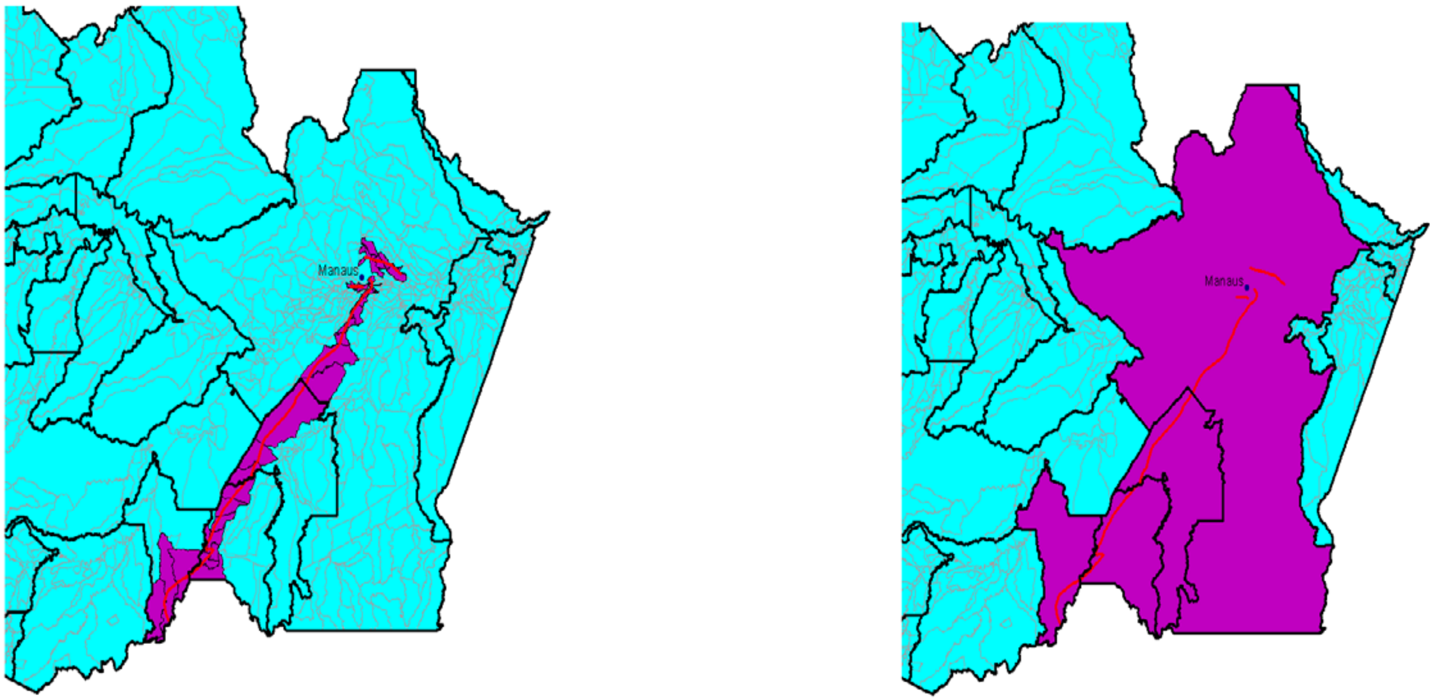
* High Prior Development: in Dev1, prior roads and prior deforestation is > 25%; in Dev2, any prior deforestation.
Intermediate Prior Development: always defined as all of the tracts with lower than 'High' but higher than 'Low'.
Low Prior Development: in Dev1, no prior roads, prior deforestation up to 25%; in Dev2, no prior deforestation.
For neighbor investment: in Dev 1, none in tracts with centroids <= 100km; in Dev2, none in tracts out to 200km.

** Dependent Variable = forest hazard rate = area deforested 1986-1992 divided by tract's initial (1986) forest area. Weights are the tracts' initial forest areas. Regression coefficients are presented with pvalues in the parentheses. Dropping all of the census tracts with centroids within 5km of any of the locations that we define as a large city.

*** coefficient multiplied by 1000 (per kilometer instead of per meter)

<u>**Figure 1**</u>

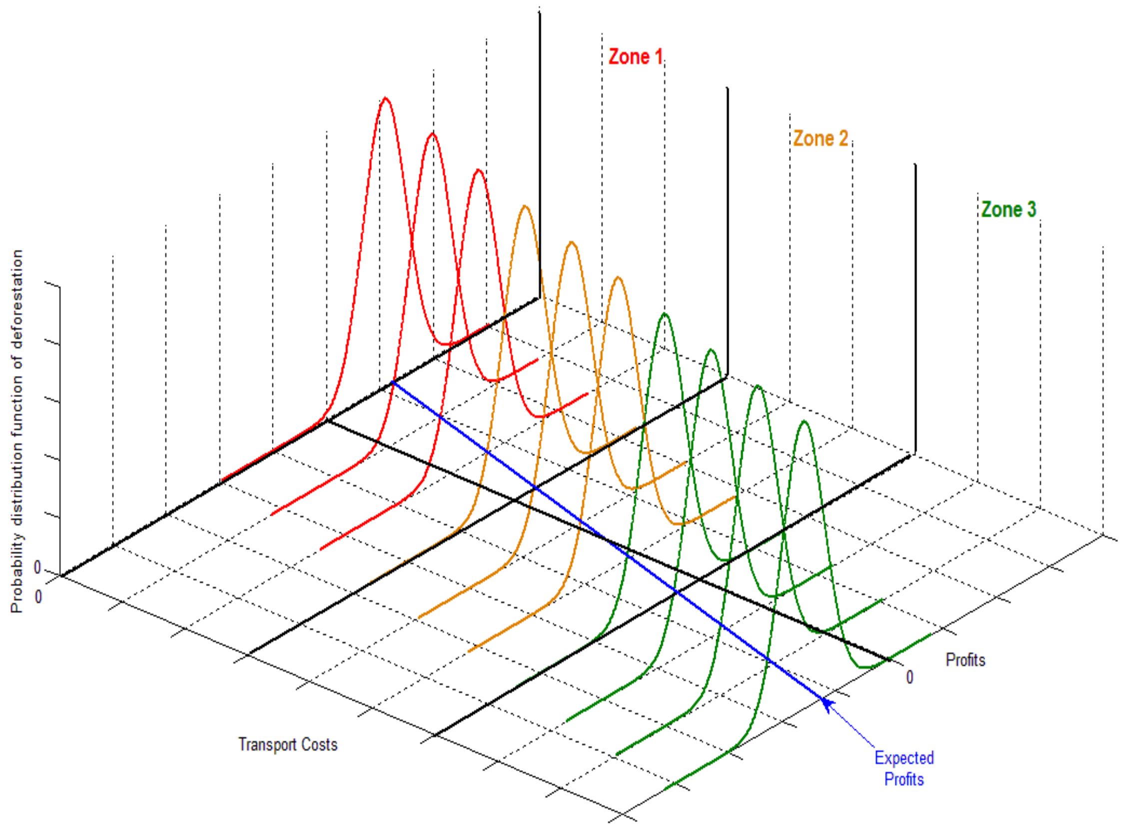
Precision Gained using Road Assignment to Census Tracts instead of Counties -- Amazonas Example



Source: authors' manipulations of roads data (see 4.1.2).

<u>**Figure 2**</u>

Model's Initial 'von Thunen' Prior-Development Landscape



<u>Figure 3</u>

Model's Predicted Short-Run Road Impacts